COMPANIONS TO ISOLATED ELLIPTICAL GALAXIES: REVISITING THE BOTHUN-SULLIVAN (1977) SAMPLE USING THE NASA/IPAC EXTRAGALACTIC DATABASE

BARRY F. MADORE

NASA/IPAC Extragalactic Database

Infrared Processing and Analysis Center

California Institute of Technology

Pasadena, CA 91125

WENDY L. FREEDMAN

Observatories of the Carnegie Institution of Washington

813 Santa Barbara St.

Pasadena, CA 91101

and

GREGORY D. BOTHUN

Department of Physics

415 Willamette Hall

University of Washington

Eugene, OR 97403

Received ....

Address for Proofs: Running Headline: *Companion Galaxies*

Barry F. Madore
NASA/IPAC Extragalactic Database
IPAC MS 100-22
Caltech
Pasadena, CA 91125

ABSTRACT

We investigate the number of physical companion galaxies for a sample of relatively isolated elliptical galaxies. The *NASA/IPAC Extragalactic Database* (NED) has been used to reinvestigate the incidence of satellite galaxies for a sample of 34 elliptical galaxies, first investigated by Bothun & Sullivan (1977) using a visual inspection of Palomar Sky Survey prints out to a projected search radius of 75 kpc. We have repeated their original investigation using data cataloged data in NED. Nine of these ellipticals appear to be members of galaxy clusters: the remaining sample of 25 galaxies reveals an average of +1.0 ± 0.5 apparent companions per galaxy within a projected search radius of 75 kpc, in excess of two equal-area comparison regions displaced by 150-300 kpc. This is nearly an order of magnitude larger than the +0.12 ± 0.42 companions/galaxy found by Bothun & Sullivan for the identical sample. Making use of published radial velocities, mostly available since the completion of the Bothun-Sullivan study, identifies the physical companions and gives a somewhat lower estimate of +0.4 companions per elliptical. This is still a factor of 3× larger than the original statistical study, but given the incomplete and heterogeneous nature of the survey redshifts in NED, it still yields a firm lower limit on the number (and identity) of physical companions. An expansion of the search radius out to 300 kpc, again restricted to sampling only those objects with known redshifts in NED, gives another lower limit of 4.3 physical companions per galaxy. (Excluding five elliptical galaxies in the Fornax cluster this average drops to 3.5 companions per elliptical.) These physical companions are individually identified and listed, and the ensemble-averaged radial density distribution of these associated galaxies is presented. For the ensemble, the radial density distribution is found to have a fall-off consistent with $\rho \propto \mathrm{R}^{-0.5}$ out to approximately 150 kpc. For non-Fornax cluster companions the fall-off continues out to the 300-kpc limit of the survey. The velocity dispersion of these companions is found to be constant with projected radial distance from the central elliptical, holding at a value of approximately $\sigma \sim \pm 300 - 350$ km/sec

overall.

1. INTRODUCTION

Recently, the numbers of satellite galaxy companions to galaxies have received renewed interest in the context of cold dark matter (CDM) models for structure formation where the theoretical expectation of the models exceeds the observed companions by approximately a factor of 100 (*e.g.,* Moore *et al.* 1999; Klypin *et al.* 1999). This large number of expected companions results from the relative inefficiency of the galaxy amalgamation process from CDM seeds in which each large mass (10^12) is surrounded by a large relic population. Given the nature of large scale structure, this relic population can either be confined to the group/cluster potential, or bound to individual large galaxy halos. In addition, the incidence of physical companions can provide an important constraint on the merger history of galaxies and/or the role that dynamical friction plays in adding additional material to galaxies after they have formed. The lack of any observational counterpart to the theoretical expectation may be somewhat troubling but there are a host of viable explanations for their absence. For instance, its possible that the systems are just too diffuse to be detected, that they have been essentially heated/evaporated by an ionizing UV background and/or supernova winds due to star formation in the massive galaxies.

Many years ago, Bothun & Sullivan (1977; hereafter BS77) selected out a sample of 34 elliptical galaxies for a survey of their dwarf galaxy companions. These ellipticals were defined to be isolated, based on a criterion that no other large/bright galaxy was found to be at a projected radius of 150 kpc of the elliptical. In retrospect, that isolation criteria was naive, but little was known about large scale structure at that time. Using the POSS prints and a digitizer, BS77 claimed to have searched for companions down to a limiting diameter of 0.2 arcmin, although recognizing galaxies at that limiting diameter on POSS prints is likely much more difficult than BS77 appreciated. From that survey, BS77 concluded that, statistically speaking, this sample of "isolated" elliptical galaxies had an excess of $+0.12\pm0.42$ companions, *i.e.,* indistinguishable from zero. This differed significantly when compared to a similar study by Holmberg (1969) who found $+1.08 \pm 0.37$ companions around selected spiral galaxies. Both studies utilized the POSS prints and statistical background fields that were selected to lie relatively near the target galaxy. Again, given our knowledge of the extent of large scale clustering, the control fields were, in general, placed too near the target galaxy.

In the ensuing years the study of companions has been continued by Zaritsky and by Vader, and each of their collaborators, in a series of papers (Zaritsky, Smith, Frenk, & White 1993, 1997; Lorrimer, Frenk, Smith, White & Zaritsky 1994; Vader & Sandage 1991, Vader & Chaboyer 1997 and references therein). Zaritsky studied the kinematics of the general population of companions orbiting spiral galaxies; while Vader specifically investigated the dwarf elliptical populations around central galaxies of diverse morphological types. Conclusions of direct relevance to this paper are that nearby field spirals typically have only one or two physical companions each, and that of those the early-type dwarf-elliptical companions are more preferentially concentrated around their parent galaxies. This may be indicative of a population of bound physical companions, similar to that seen around some cD galaxies in clusters (*e.g.,* Bothun & Schombert 1990).

In this paper our interest is refocused on the companion population surrounding elliptical galaxies, specifically the 'isolated elliptical galaxies' studied by BS77. Although the procedures used in BS77 were documented, none of the surrounding galaxies counted in either investigation were individually identified or subsequently published, since the stated intent was to draw a statistical conclusion about the general incidence of companions, not to necessarily identify or follow up any particular galaxy grouping or any given (apparent) companion. The conclusion was that the environments of ellipticals and spirals were significantly different, in the sense that isolated ellipticals were statistically devoid of companions, while spirals had on average one physical companion each.

In the intervening quarter century many new surveys (2MASS, APM, etc.) to fainter limiting magnitudes have been undertaken; follow-up radial velocity surveys (UZC, 2dF, etc.) have been completed; and these published data are almost all now accessible in electronically searchable form through the *NASA/IPAC Extragalactic Database* (NED). As part of a larger, on-going program to study the general distribution of companion galaxies, we have undertaken here to first revisit the BS77 sample. However, given the fainter magnitude limits and the radial velocities now available, it seemed worthwhile to extend their investigation and to search for true physical companions, rather than simply statistical excesses. These additional surveys should provide improved sensitivity to companion detection primarily because compact galaxies, often difficult to distinguish from stars on the POSS, are often emission line galaxies (*e.g.*, Salzer, McAlpine & Boroson 1989; Bothun *et al.* 1989) that easily detected at other wavelengths (IR, UV/X-ray). Hence, NED offers us the ability to perform the kind of multi-wavelength search for companions that can greatly extend that which can be done by visual inspection alone.

Although NED taps many different surveys for galaxy detection, the nature of the radial velocity measurements for NED galaxies remains sparse and heterogeneous, so in that sense NED cannot be used to any reliable completeness level for companion searches. However, despite the patchwork nature of NED, it does have the unique characteristic of being the largest on-line collection of galaxies available, with the most complete sampling of radial-velocity data (291,000 out of 4.7 million objects in NED have published radial velocities) linked directly to the individual objects. In addition, the accessibility of these on-line data allows us to extend the BS77 companions position search to a projected radius of 300 kpc around each target galaxy thereby increasing the area surveyed by a factor of 16. All radial-velocity companions are identified and recorded, and the source density as a function of radius calculated for all velocity-confirmed companions (Table 2). The obvious advantage here is that the process is no longer statistical, as in the previous sense of differencing two large numbers in order to extract the companion signal from the background noise, but rather it is physical, and allows us to set very strict *lower* limits on the numbers, and the projected radial distances, of individually identifiable galaxies that are certainly physically associated with the 'isolated' galaxies in this sample.

II. Reworking the Bothun & Sullivan (1977) Sample

We start by repeating the BS77 experiment as closely as can be reconstructed from their published procedures. Their sample consisted of 34 elliptical galaxies originally drawn from the *Reference Catalogue of Bright Galaxies* (de Vaucouleurs and de Vaucouleurs 1964), falling north of $\delta = -45$, and having expansion velocities V $\leq$ 3,000 km/sec. This yielded a master list of 90 ellipticals, which was narrowed down to a sample of 34 after applying the aforementioned isolation criterion. Again, as in BS77, a projected search radius of 75 kpc was initially adopted (assuming $H_o = 75$ km/sec/Mpc and using the expansion velocities, corrected for Solar motion, as originally tabulated in BS77). For this sample, the search radii ranged from 9 to 14 arcmin. We do not have a diameter limit as in the BS77 study, since these are not available within NED; however, our aim is simply to search for potential companions, regardless of diameter. To assess the field-galaxy contamination rate around each target galaxy, we searched two equivalent circular areas 20-40 arcmin to the north and to the south of the primary position (BS77 used similar comparison regions, but chose to place them to the east and west of the central elliptical. Our north-south positioning was done for computational simplicity, but should be statistically equivalent.) Searches were undertaken interactively. The version of NED searched had a public release date of 06 Dec 2001. Table 1 lists the results. Columns 1 and 10 identify the elliptical galaxy under consideration. Column 2 gives the total counts (in the 75 kpc circular area = N75), while columns 3 and 4 give the field counts ([N] and [S], to the north and south, respectively. The statistical excess and its associated counting error, is listed in column 5. For comparison the numbers quoted on a galaxy-by-galaxy basis by BS77 are given in column 6, followed by the redshift in column 7. Columns 8 and 9 then give the number of radial-velocity-confirmed companions inside 75 and 150 kpc search radii, respectively (see Section III.)

We find that within the 75 kpc search radius the isolated elliptical-galaxy sample has on average $+0.74 \pm 0.95$ cataloged companions per elliptical. This is the result of differencing two rather large numbers (529 objects on target minus an average of 504 galaxies in the equal-area comparison fields), as confirmed by the large statistical uncertainty quoted. However, the result differs for galaxies inside and outside of clusters. We note that several of the galaxies (NGC 1351, NGC 1395, NGC 1426, NGC 1427 and NGC 1439) are probably members of the Fornax cluster. In addition, NGC 3640, NGC 3818, NGC 4697 and NGC 6958 are each projected upon regions of the sky where galaxy counts are particularly rich and deep, and may also be in loose clusters themselves (the NGC 3640 Group and Abell S0900, in particular). Examining the remaining 25 ellipticals the source density of companions rises in both absolute terms and in relative significance to $+0.96\pm$ 0.54 companions per elliptical. This is nearly one order of magnitude higher in density than the result quoted by BS77 of 0.12 ± 0.42 companions/galaxy. To first order, this indicates that the procedure used here, which accesses multiple galaxy catalogs, has a much higher detection efficiency than the visual approach adopted by BS77.

III. Looking Beyond a 75 Kpc Radius

We went through the BS77 sample a second time, increasing the search radius a factor of 4×) (i.e., out to 300 kpc, which is equivalent to approximately half the distance from the Milky way to M31.) However, we included only those galaxies with cataloged radial velocities commensurate with them being physically associated with the central elliptical galaxy (i.e., generally within ±1,000 km/sec) were counted and retained for further analysis and tabulation.

Table 2 lists the parent galaxy, each of its radial-velocity confirmed (physical) companions, their radial separations from the central elliptical (in arcmin), and their differential radial velocities (in the sense of companion minus central elliptical). Physical companions falling within the original BS77 search radius of 75 kpc are marked with an asterisk. The central velocity dispersion of the parent elliptical galaxy is given in parentheses following the galaxy name.

For the entire sample of 34 E galaxies we find 147 other galaxies located within a projected radius of 300 kpc and having published redshifts within ±1,000 km/sec of the central parent galaxy. While the variation is large (ranging from a low of 0, to a high of 23 associated galaxies per central elliptical) the average number of companions is 4.3 per elliptical. Previously quoted statistical (counting) uncertainties do not apply here: this is a lower limit on the number of companions, with the uncertainty dominated by cosmic variance and survey systematics.

We now examine the radial density distribution of these physically associated galaxies. Figure 10 shows the ensemble radial density fall-off as a function of normalized distance (R_{300} = R/300 kpc). If it were not for the fact that these galaxies are all radial-velocity confirmed to be physically associated with the central elliptical, it would be tempting to suggest that there is some background (contamination) level at which the counts are going flat at large radii. However, these galaxies are in all probability actual physical companions. Therefore, it is likely that the general population of galaxies associated with these central ellipticals could extend even further out beyond 300 Kpc. Alternatively put, the elliptical galaxies may not be all that isolated to begin with and what we may be seeing here is the background level of their association with a more widely distributed cluster population.

To some degree this observation may explain why the BS77 number is so low. It is reasonable to assume that they were differencing out physical companions by having their comparison field in so close to the parent galaxy that they had were not yet sampling the pure field contamination population. Given that most of the comparison fields in BS77 had only a average of 2 galaxies counted (and a maximum of 10 in two fields combined) the vagaries of small number statistics become problematic.

That said, it may also be true that our adopted velocity difference is too generous and tends to exaggerate the number of physical companions by being overly inclusive, especially in the the outskirts of clusters. Indeed, the effect of narrowing the velocity window down to ±300 km/sec results in the loss of 51 companions from the 300 kpc sample, and correspondingly drops the average number of 'physical' companions down to 2.8 companions per elliptical.

IV. Discussion

Because of the inherent inhomogeneity of the NED holdings of both objects over the sky and radial velocities of selected subsets, little can be said about the absolute total numbers of galaxies physically associated with the 'isolated' ellipticals in the BS77 sample; however, strict lower limits are obtained here. That is to say, the galaxies found to be radial-velocity companions now will not go away with deeper surveys, with better statistics, or with more homogeneous studies. We therefore conclude that this sample of galaxies has 14 currently known physically associated companions, amounting to a lower-limit average of 0.4 ± companions/galaxy within 75 kpc. Within a 300 kpc radius these numbers increase to 147 galaxies around 34 central objects, yielding at least 4.3 companions/galaxy. Excluding the five galaxies (NGC 1351, 1395, 1426, 1427 and 1439) in the Fornax Cluster, gives an average of 3.5 companions per central galaxy.

It is of interest to use the satellites as probes of the halo mass and calculate the mass M interior to the last radial bin, R_max. Using the simplest assumptions and assuming a relaxed equilibrium state one estimate of the mass can be obtained from $M = \frac{3R_{max}\sigma_r^2}{2G}$, where σ_r is the observed radial-velocity dispersion and G is the gravitational constant. Adopting a value of 300 km/s as representative of the observed velocity dispersion, at a conservative distance of 100 kpc, the derived total mass $M_{100\ kpc}$ is calculated to be in excess of $3 \times 10^{12} M_\odot$. This can only be considered an indicative mass, given the wide range of possible mass models that can be used in inverting the projected velocity dispersion. In this regard the interested reader is referred to the more extensive modeling and discussion by Zaritsky & White (1994).

The radial fall-off in satellite surface density Σ is consistent with the general correlation function (binned) down to 30 kpc, with $\Sigma \sim R^\alpha$ where $\alpha = -0.5$. This is entirely consistent with the almost identical conclusion drawn by Lake & Tremaine (1980) for the Holmberg (1969) spiral-galaxy companion data, from which they and found α = -0.5 held from 40 kpc down to scales as small as 5 kpc. A significantly steeper slope to the radial fall-off profile is quoted by Vader & Sandage (1991), where $\alpha = -1.22 \pm 0.05$ for r = 16-270 kpc (corrected to $H_o = 75$ km/sec/kpc) for early-type dwarf companions around selected E/S0 galaxies, gleaned from a visual inspection of photographic plates used to construct the RSA and the *Carnegie Atlas.*

The analysis of BS77 predicts that within the entire sample of 34 isolated ellipticals only 4 (0.12×34) galaxies will prove to be physical companions. Based on incomplete published radial velocity data we find that there are at least 14 radial-velocity confirmed companions. As probes of the gravitational field or as indicators of the average number of companions per elliptical galaxy the present study indicates that there are at least as many companions in the vicinity of ellipticals (0.4 to 1.0 companions per galaxy in the inner 75 kpc, and at least 4 companions per galaxy in the surrounding 300 kpc sphere) as there are around spiral galaxies (if Holmberg's statistical numbers, giving 1.1 companions/spiral within 75 kpc, are fiducial.)

And finally, using the physical companions with published radial velocities and differencing them against the redshift of the central elliptical we can look at the class-averaged fall-off of the one-dimensional velocity dispersion as a function of radius, and calculate the total enclosed mass at any given radius. Figure 12 shows the data.

In sum, we have demonstrated that the NASA/IPAC Extraglactic Database is a useful resource for investigating the environments of galaxies as multi-wavelength surveys continue to detect new galaxies. As a consequence, this updated catalog gives a much more robust measure of the phase-space density of galaxies in small targeted volumes, compared with earlier published visual estimates. We have used this technique to upgrade and update the results of BS77 with respect to physical companions around "isolated" elliptical galaxies. This new analysis clearly shows the limitations of the BS77 approach. In particular, the visual approach to galaxy detection adopted by BS77 did not find all the surrounding galaxies, and was not able to identify individual physical companions. Furthermore, their early understanding of large scale structure compromised even their statistical comparisons. Using a better defined sample and the now available redshift information, our new analysis has shown that most ellipticals do have at least three physical companions bound by a relatively velocity dispersion of ±300-350 km/s, inside a radius of 300 kpc. The ensemble properties of these physical companions are consistent with total halo masses of $1 - 3 \times 10^{12} M_\odot$.

Acknowledgements

This research was exclusively undertaken using the tools and data provided by the 21 Dec 2001 release of the WEB-based version of the NASA/IPAC Extragalactic Database (NED), which is operated by the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration.

References

Bothun, G.D., Halpern, J.P., Lonsdale, C.J., Impey, C., & Schmitz, M. 1989, ApJS, 70, 271

Bothun, G.D., & Schombert, J.M. 1990, ApJ, 360, 436

Bothun, G.D., & Sullivan, W.T. 1977, PASP, 89, 5 (BS77)

Dressler, A., Schechter, P.L., & Rose, J.A. 1986, AJ, 91, 1058

Holmberg, E.E. 1969, Arkiv. Astr., 5, 305

Klypin, A., Kravtsov, A.V., Valenzuela, O., & Prada, F. 1999 ApJ, 522, 82

Lake, G., & Tremaine, S. 1980, ApJL, 238, 13

Lorrimer, S.J., Frenk, C.S., Smith, R.M., White, S., & Zaritsky, D. 1994, MNRAS, 269, 696

Moore, B., Ghigna, S., Governato, F., Lake, G., Quinn, T., Stadel, J., & Tozzi, P. 1999, ApJL, 524, 19

Salzer, J.I., McAlpine, G.M. & Boroson, T.A. 1989, ApJS, 70, 447

Sandage, A.R., & Bedke, J. 1994, *The Carnegie Atlas of Galaxies,* Volumes I & II, Carnegie Institution of Washington

Sandage, A.R., & Tammann, G.A., 1981, *Revised Shapley-Ames Catalog of Bright Galaxies,* Carnegie Institution of Washington, Publ. 635

Vader, J.P., & Chaboyer, B. 1992, PASP, 104, 57

Vader, J.P., & Chaboyer, B. 1994, AJ, 108, 1209

Vader, J.P., & Sandage, A.R. 1991, ApJL, 371, 1

Zaritsky, D., Smith, R.M., Frenk, C.S., & White, S. 1993, ApJ, 405, 464

Zaritsky, D., Smith, R.M., Frenk, C.S., & White, S. 1997, ApJ, 478, 39

Zaritsky, D., & White, S. 1994, ApJ, 435, 599

Appendix: Comments on Individual Systems

NGC 0584

NGC 0584 has one certain physical companion, NGC 0580, within the original 75 kpc search radius. BS77 noted a second optical companion. Visual inspection strongly suggests that the object, 2MASXi J0130541-064941 (diametrically opposite to NGC 0580 across the central E galaxy) is also a physical companion based on its size, proximity and morphology. No redshift yet exists for this 2MASS object, but follow-up studies of it would be useful.

Although NGC 0584 is the dominant member (in linear extent and luminosity) of a small chain of galaxies, it is interesting to note that all of the members with measured radial velocities have a positive redshift with respect to NGC 0584, suggesting that the elliptical is not the center of gravity of this grouping and that the velocities are probing a wider potential. Similar comments apply to several other groupings in this paper: All of the companions associated with NGC 1052 have negative radial velocities with respect to the elliptical under study. NGC 4697 has five companions, and NGC 3640 has 8 companions, and NGC 5322 has 4 companions, all of which have positive radial velocities with respect to their associated elliptical.

NGC 0720

This galaxy and its retinue of companions was studied extensively by Dressler, Schechter & Rose (1986). Their companion No. 14 (PGC 006960), as well as one of Vader & Charboyer's (1994) objects, [VC94] 015113-1403.0 are good candidates for being physical companions. Indeed, two other galaxies, KUG 0147-138 (ΔV = –556 km/sec) and DDO 015 (ΔV = +35 km/sec), are also likely physical companions, albeit somewhat further afield than our 300 kpc radial cut-off, being found 50 arcmin (345 kpc) and 73 arcmin (505 kpc) away from NGC 0720, respectively.

NGC 1052

In addition to the two radial-velocity confirmed objects, a visual inspection of the 75-kpc field surrounding NGC 1052 reveals two other highly likely companions which presently do not have confirming radial velocity data. They are [KKS2000] 04, a fine low-surface-brightness dwarf spheroidal, to the south-east, and 2MASXi J0241351-081024 to the north-east. However, the grand-design spiral galaxy NGC 1042 is only 15 arcmin away, suggesting that the elliptical, NGC 1052, is by no means isolated, but may share the potential with at least two other sizeable galaxies, the other being NGC 1035. This mixed-morphology triplet has already been cataloged, and is known as KTS 018.

We also suggest that [VC94] 023858-0820.4 (which has a radial velocity, but at its published position has no obvious identification) should be identified with 2MASXi J0241351-081024.

NGC 4589

There is a dwarf galaxy, [HS98] 162, about 5 arcmin to the north-west. It is a prime candidate for being a physical companion, and for a follow-up radial velocity measurement.

NGC 5812

A visual inspection of the POSS image surrounding NGC 5813 reveals two prime candidates for physical companions (and radial velocity followup) that have gone unlisted in previous surveys. These are NGC 5812:[MFB03] 1 a nucleated (dNE) dwarf at RA(2000) = 15:00:55, DEC(2000) = -07:24:59, and NGC 5812:[MFB03] 2 at RA(2000) = 15:00:48, DEC(2000) = -07:27:42.

Figure Captions

Fig. 1 – The 75 kpc region around NGC 0584. The field of view shown here, and in the following eight figures, is set to the same physical size of 75 kpc on a side. The two radial-velocity-confirmed galaxies, 2MASXi J0130541-064941 and NGC 0586 are labeled.

Fig. 2 – The 75 kpc region around NGC 1052. Only radial-velocity-confirmed companions are labeled, with the exception of the giant low-surface-brightness object [KKS2000] 04, and the 2MASS object which, as noted in the Appendix, is thought by us to be the same as the [VC94] galaxy which has a published radial velocity (but no obvious optical counterpart on the POSS). Note the large spiral galaxy, NGC 1042 just outside the 75 kpc radius in the lower right corner of the frame.

Fig. 3 – The 75 kpc region around NGC 3348. The single radial-velocity-confirmed galaxy MCG +12-10-079 is labeled.

Fig. 4 – The 75 kpc region around NGC 3640. The single radial-velocity-confirmed galaxy NGC 3641 is labeled.

Fig. 5 – The 75 kpc region around NGC 3818. The single radial-velocity-confirmed galaxy 2dFGPS N113Z117 is labeled.

Fig. 6 – The 75 kpc region around NGC 4125. The single radial-velocity-confirmed galaxy NGC 4121 is labeled.

Fig. 7 – The 75 kpc region around NGC 4589. The single radial-velocity-confirmed galaxy NGC 4572 is labeled.

Fig. 8 – The 75 kpc region around NGC 5812. The single radial-velocity-confirmed galaxy IC 1084 is labeled.

Fig. 9 – The 75 kpc region around NGC 5831. The two radial-velocity-confirmed galaxies, NGC 5846:[ZM98] 0028 and NPM1G +01.0437 are labeled.

Fig. 10– The radial density distribution for the entire ensemble of radial-velocity-confirmed companions to 34 isolated ellipticals. The solid line has a slope of unity, while the dashed line has the slope of -1.22 as suggested by Vader & Sandage (1991) in their study of companions to RSA galaxies. A fall-off is apparent no further than 100 kpc after which the density of companions appears to be relatively constant.

Fig. 11– The run of velocity dispersion as a function of distance from the central elliptical galaxy. Circled dots are the 48 radial-velocity companions along the line of sight to the five Fornax cluster ellipticals. Vertical error bars represent the $\pm 1 -$ sigma velocity dispersion calculated in each of the 5 bins, of width 140 kpc; numerical values are shown in square brackets below each error bar. The generally smaller numbers above them are the dispersions calculated for the non-Fornax sample (plotted as simple filled circles). No change in velocity dispersion with radial separation from the central elliptical is apparent for either sample.

TABLE 1

Companion-Galaxy Counts within R = 75 Kpc of 'Isolated' Ellipticals

Name (1)	N75 (2)	[N] (3)	[S] (4)	Excess (5)	BS77 (6)	V (7)	S (8)	L (9)	Name (10)
NGC 0584	4	1	1	+3.0±2.2	+1.5	1,885	1	4	NGC 0584
NGC 0636	3	3	2	+0.5±2.3	−1.0	1,941	1	1	NGC 0636
NGC 0720	1	0	6	−2.0±2.0	+0.0	1,808	0	2	NGC 0720
NGC 0821	2	0	0	+2.0±1.4	−1.5	1,778	0	0	NGC 0821
NGC 1052	4	3	8	−1.5±3.1	−0.5	1,460	2	4	NGC 1052
NGC 1351	80	80	96	−8.0±13.0	+0.5	1,589	0	8	NGC 1351
NGC 1395	39	60	42	−12.0±9.5	+0.0	1,721	0	5	NGC 1395
NGC 1426	4	1	25	−9.0±4.1	+1.5	1,358	0	8	NGC 1426
NGC 1427	134	75	60	+65.5±14.2	−0.5	1,681	2	23	NGC 1427
NGC 1439	2	3	6	−2.5±2.5	+1.5	1,997	0	2	NGC 1439
NGC 2768	5	0	1	+4.5±2.3	+0.0	1,408	0	3	NGC 2768
NGC 2974	6	1	2	+4.5±2.7	+0.5	2,013	0	0	NGC 2974
NGC 2986	3	0	0	+3.0±1.7	+1.0	2,397	0	0	NGC 2986
NGC 3078	0	0	0	+0.0±0.0	−1.0	2,481	0	3	NGC 3078
NGC 3348	2	1	6	−1.5±2.3	+0.0	2,855	1	2	NGC 3348
NGC 3585	0	0	1	−0.5±0.7	+0.0	1,491	0	1	NGC 3585
NGC 3610	1	0	3	−0.5±1.6	−0.5	1,765	0	7	NGC 3610
NGC 3613	3	2	2	+1.0±2.2	−0.5	2,054	0	8	NGC 3613
NGC 3640	15	15	50	−17.5±6.9	+0.5	1,354	1	8	NGC 3640
NGC 3818	46	80	49	−18.5±10.5	+1.0	1,498	1	3	NGC 3818
NGC 3904	1	0	1	+0.5±1.2	+0.5	1,614	0	4	NGC 3904
NGC 3923	5	0	1	+4.5±2.3	+1.5	1,788	0	5	NGC 3923
NGC 3962	3	3	4	−0.5±2.5	−0.5	1,794	0	0	NGC 3962
NGC 4125	9	2	2	+7.0±3.3	+3.0	1,365	1	2	NGC 4125
NGC 4494	20	18	24	−1.0±6.4	−0.5	1,321	0	0	NGC 4494
NGC 4589	9	1	3	+7.0±3.3	+0.5	1,825	1	5	NGC 4589
NGC 4697	81	85	96	−9.5±13.1	−2.0	1,308	0	6	NGC 4697
NGC 4742	6	9	10	−3.5±3.9	−3.5	1,312	0	7	NGC 4742
NGC 5061	3	5	6	−2.5±2.9	−0.5	2,065	0	0	NGC 5061
NGC 5322	4	3	6	−0.5±2.9	+0.5	1,902	0	4	NGC 5322
NGC 5812	1	0	0	+1.0±1.0	+2.0	2,066	1	3	NGC 5812
NGC 5813	3	0	0	+3.0±1.7	+1.0	1,822	0	5	NGC 5813
NGC 5831	6	2	7	+1.5±3.2	−0.5	1,684	2	11	NGC 5831
NGC 6958	24	29	25	+9.5±13.1	−2.0	2,757	0	1	NGC 6958

TABLE 2

Velocity-Confirmed Companions within R = 300 kpc

Central E Companion(s)	R (arcmin)	ΔV (km/sec)
NGC 0584 ($\sigma_c = \pm 225$ km/sec)		
NGC 0586 *	4.3	+188
IC 0127	24.0	+193
NGC 0596	24.7	+74
NGC 0600	37.2	+40
NGC 0636 ($\sigma_c = \pm 167$ km/sec)		
MCG -01-05-012 *	16.8	+96
NGC 0720 ($\sigma_c = \pm 237$ km/sec)		
KUG 0150-138	11.3	–371
LEDA 087905	14.8	–249
LEDA 087906	18.6	–512
MCG -02-05-074	27.7	+197
LEDA 087900	30.7	–338
MCG -02-05-072	34.4	–322
NGC 0821 ($\sigma_c = \pm 209$ km/sec)		
n/a	...	...
NGC1052 ($\sigma_c = \pm 215$ km/sec)		
[VC94] 023858-0820.4 *	9.3	–58
NGC 1047 *	10.2	–130
NGC 1042	14.7	–102
NGC 1035	24.8	–229
NGC1351 ($\sigma_c = \pm 147$ km/sec)		
FCC 100	19.1	+146
NGC 1351A	29.2	–154
MCG -06-08-025	30.4	–111
ESO 358-015	31.3	–126
FCC 085	41.7	–5
FCCB 905	44.0	–236
ESO 358-006	45.0	–177
LSBG F358-61	45.9	+609
NGC1395 ($\sigma_c = \pm 248$ km/sec)		
ESO 482-017	12.8	–371
NGC 1401	21.8	–199
ESO 482-018	23.7	–30
ESO 482-031	37.8	–96
NGC 1416	39.8	+450

TABLE 2 (cont.)

Velocity-Confirmed Companions within R = 300 kpc

Central E Companion(s)	R (arcmin)	ΔV (km/sec)
NGC 1427 ($\sigma_c = \pm170$ km/sec)		
CGF 10-18 *	0.1	+28
FCCB 1554 *	4.9	+347
FCC 274	8.9	–315
NGC 1428	14.3	+252
FCC 264	15.3	+645
FCC 266	15.4	+170
LSBG F358-33	26.4	+129
FCC 252	28.0	–111
FCC 296	29.7	–693
NGC 1427A	29.8	+640
FCC 245	30.9	+789
ESO 358-051	31.7	+346
NGC 1436	31.9	–1
FCSS J033935.9-352824	33.7	+532
FCSS J033952.5-350424	35.6	–68
LSBG F358-36	36.6	–701
ESO 358-060	36.8	–585
AM 0337-353	37.9	–536
AM 0337-355	41.7	–486
FCSS J033854.1-353333	43.0	+203
NGC 1404	43.9	+559
NGC 1399	47.0	+37
FCC 230	47.4	–239

TABLE 2 (cont.)

Velocity-Confirmed Companions within R = 300 Kpc

Central E Companion(s)	R (arcmin)	ΔV (km/sec)
NGC 1426 ($\sigma_c = \pm153$ km/sec)		
2MASXi J0341270-222822	29.0	+827
NGC 1439	30.2	+227
NGC 1422	31.4	+194
ESO 548-070	31.5	–21
NGC 1414	35.2	+238
NGC 1415	35.2	+142
ESO 482-031	39.9	+178
NGC 1416	44.1	+724
NGC 1439 ($\sigma_c = \pm159$ km/sec)		
NGC 1426	30.2	–227
ESO 549-006	44.2	–61
NGC 2768 ($\sigma = \pm194$ km/sec)		
CGCG 288-027 NED01	16.5	–236
NGC 2742	40.3	–84
NGC 2726	50.5	+145
NGC 2974 ($\sigma_c = \pm220$ km/sec)		
n/a	...	...
NGC 2986 ($\sigma_c = \pm268$ km/sec)		
n/a	...	...
NGC 3078 ($\sigma_c = \pm237$ km/sec)		
ESO 499-032	14.8	–45
NGC3048	15.3	+47
ESO 499-022	32.9	–282
NGC 3348 ($\sigma_c = \pm237$ km/sec)		
MCG +12-10-079 *	2.5	–1,829
NGC 3364	25.6	–106
NGC 3585 ($\sigma_c = \pm216$ km/sec)		
ESO 503-007	40.0	+188

TABLE 2 (cont.)

Velocity-Confirmed Companions within R = 300 Kpc

Central E Companion(s)	R (arcmin)	ΔV (km/sec)
NGC 3610 ($\sigma_c = \pm 167$ km/sec)		
SBS 1114+587	19.2	–102
UGC 06304	26.5	+66
UGC 06335	31.4	+1,231
NGC 3642	34.6	–108
SBS 1120+591	39.6	–73
NGC 3613 ($\sigma_c = \pm 213$ km/sec)		
NGC 3619	15.7	–434
NGC 3625	20.1	–47
UGC 06344	21.1	–53
UGC 06304	22.0	–225
SBS 1119+583	30.5	–364
SBS 1118+578A	32.7	+176
SBS 1114+587	33.2	–393
SBS 1118+578B	34.8	+176
NGC 3640 ($\sigma_c = \pm 184$ km/sec)		
NGC 3641 *	2.5	+441
NGC 3643	14.0	+529
NGC 3630	20.5	+171
UM 442	44.2	+293
UGC 06345	44.5	+288
NGC 3664A	49.5	+12
NGC 3664	49.8	+68
UGC 06417	49.9	+50
NGC 3818 ($\sigma_c = \pm 198$ km/sec)		
2dFGPS N113Z117 *	4.0	+186
UGCA 242	21.4	+27
LCRS B113807.1-053433	26.4	–231

TABLE 2 (cont.)

Velocity-Confirmed Companions within R = 300 Kpc

Central E / Companion(s)	R (arcmin)	ΔV (km/sec)
NGC 3904 ($\sigma_c = \pm 200$ km/sec)		
NGC 3923	36.9	+292
ESO 440-014	37.9	+603
2MASXi J1151382-284734	43.1	−103
ESO 440-023	44.7	+386
NGC 3923 ($\sigma_c = \pm 241$ km/sec)		
2MASXi J1151382-284734	8.1	−395
ESO 440-014	15.2	+311
ESO 440-023	27.6	+94
UGCA 250	34.6	−86
NGC 3904	36.9	−292
NGC 3962 ($\sigma_c = \pm 225$ km/sec)		
n/a	...	...
NGC 4125 ($\sigma_c = \pm 233$ km/sec)		
NGC 4121 *	3.7	+841
NGC 4081	49.6	+88
NGC 4494 ($\sigma_c = \pm 155$ km/sec)		
n/a	...	...
NGC 4589 ($\sigma_c = \pm 225$ km/sec)		
NGC 4572 *	7.5	+225
NGC 4648	22.3	−506
UGC 07844	31.7	−117
UGC 07767	32.0	−698
UGC 07745	33.5	−790
NGC 4697 ($\sigma_c = \pm 174$ km/sec)		
MCG -01-33-007	14.9	+91
DDO 148	32.8	+100
2MASXi J1250191-052146	36.7	+292
DDO 146	46.3	+234
NGC 4731	50.6	+254
NGC 4731A	60.0	+256

TABLE 2 (cont.)

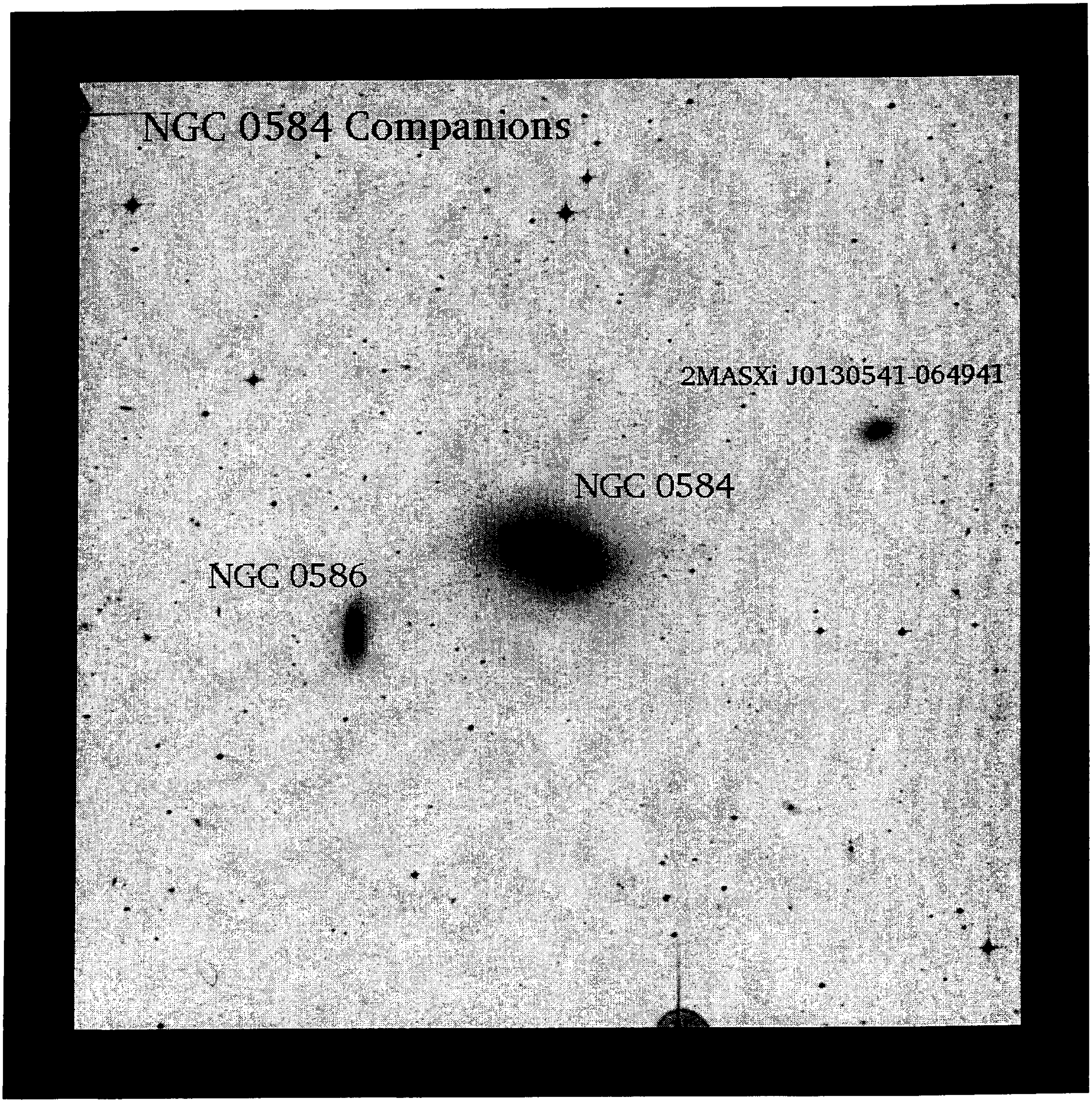
Velocity-Confirmed Companions within R = 300 Kpc

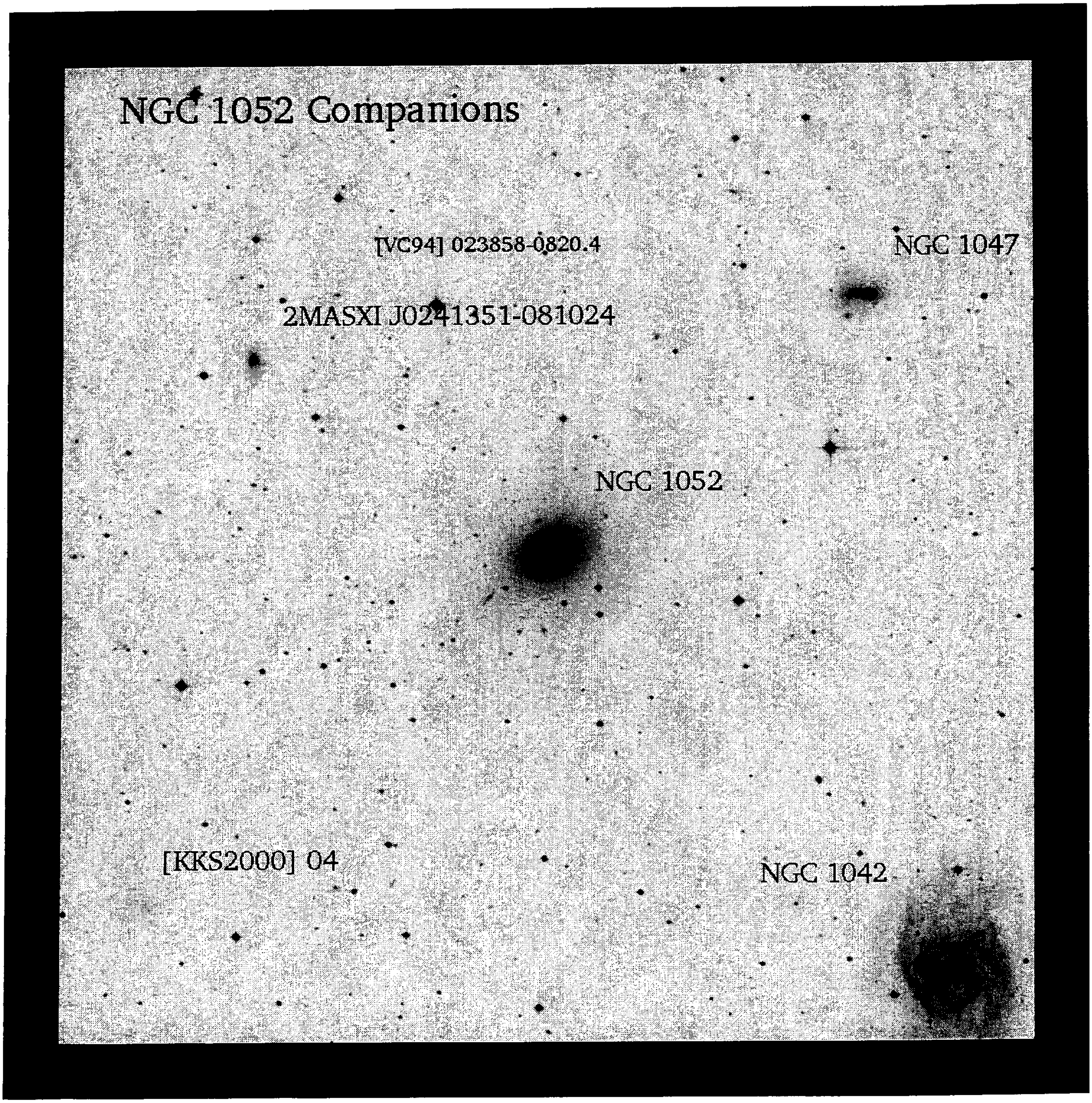
Central E Companion(s)	R (arcmin)	ΔV (km/sec)
NGC 4742 ($\sigma_c = \pm 102$ km/sec)		
NGC 4757	17.6	–400
NGC 4781	38.6	–10
MCG -06-33-015	40.8	+48
[KEB] J124959.6-093036	42.1	–423
NGC 4784	42.6	–10
NGC 4790	46.9	+87
UGC 308	55.0	52
NGC 5061 ($\sigma_c = \pm 194$ km/sec)		
n/a	...	...
NGC 5322 ($\sigma_c = \pm 234$ km/sec)		
UGC 08716	21.0	+282
UGC 08741	21.4	+279
UGC 08714	23.2	+263
NGC 5342	25.5	+430
NGC 5812 ($\sigma_c = \pm 213$ km/sec)		
IC 1084 *	5.0	+228
LCRS B145849.9-064423	32.3	–70
MCG -01-38-014	33.6	+165

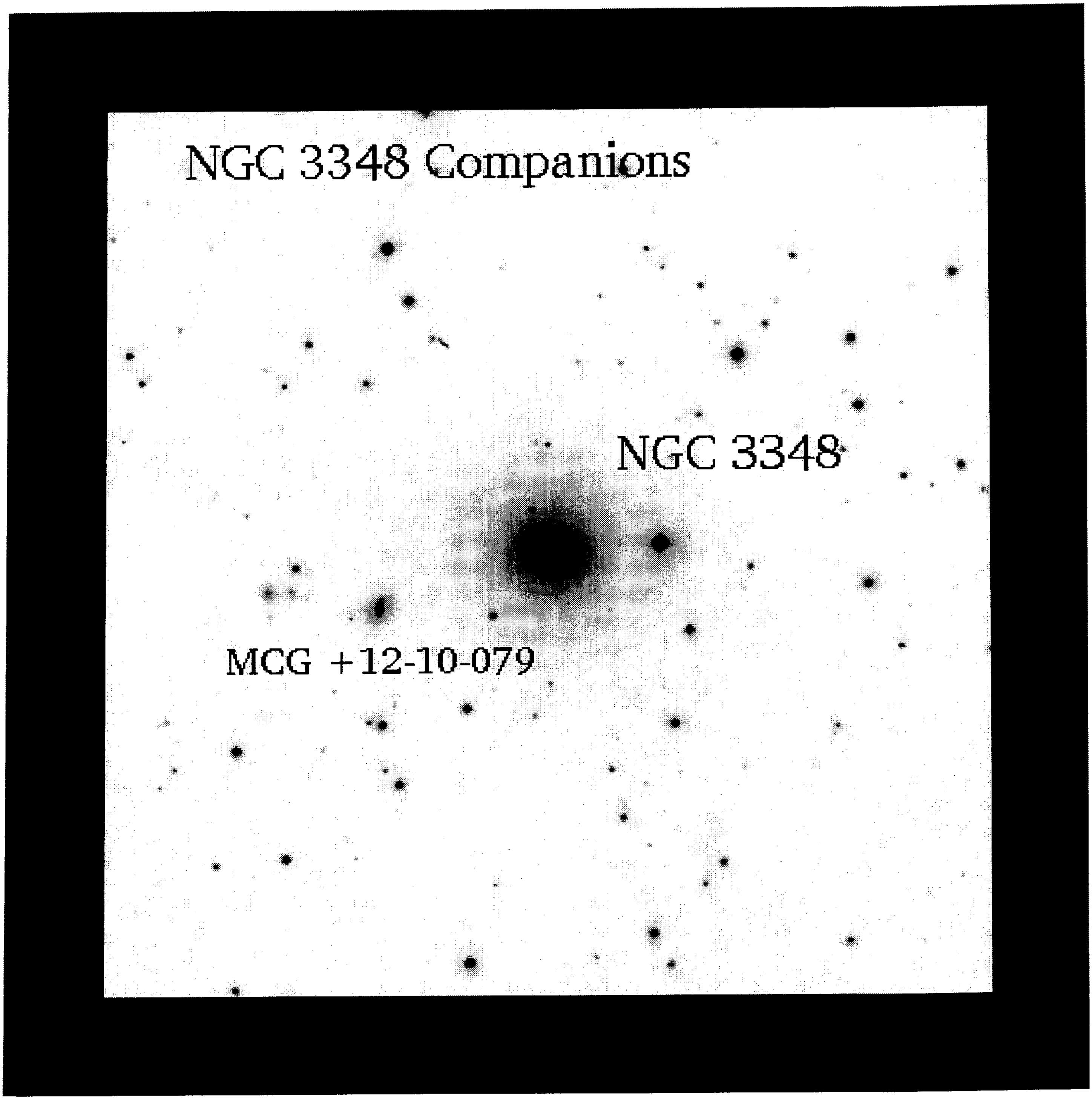
TABLE 2 (cont.)

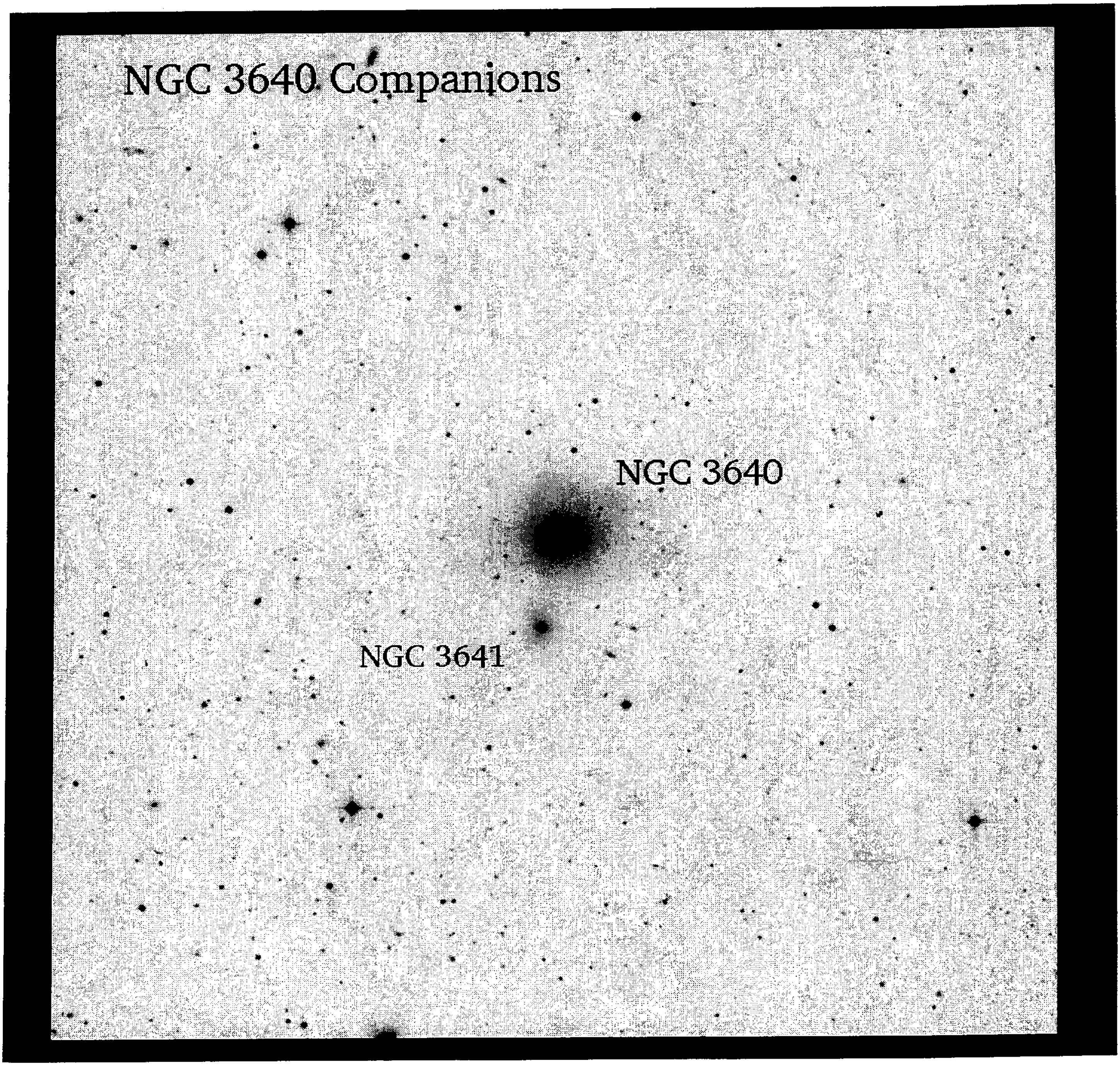
Velocity-Confirmed Companions within R = 300 Kpc

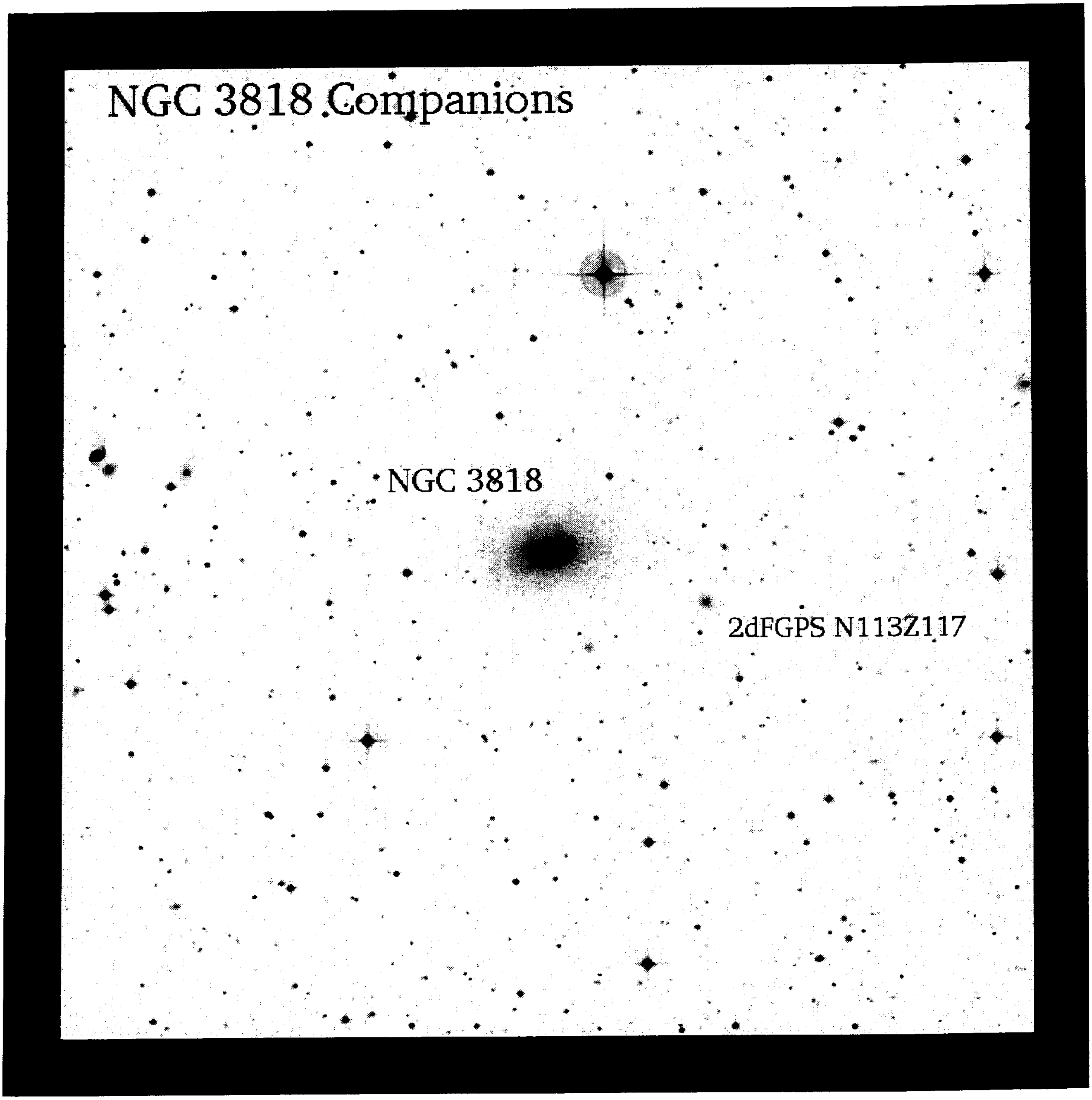
Central E Companion(s)	R (arcmin)	ΔV (km/sec)
NGC 5813 ($\sigma = \pm 230$ km/sec)		
NGC 5811 NED02	11.9	–471
NGC 5811 NED01	12.1	–471
UGC 09661	15.5	-730
NGC 5806	21.0	-613
CGCG 020-042	38.4	-153
NGC 5831 ($\sigma = \pm 168$ km/sec)		
NPM1G +01.0437 *	7.0	-90
NGC 5846:[ZM98] 0028 *	9.9	+310
NGC 5846:[ZM98] 0017	15.2	+346
NGC 5846:[ZM98] 0021	18.3	+208
NGC 5846:[ZM98] 0033	20.8	+647
NGC 5846:[ZM98] 0039	23.2	+477
NGC 5846:[ZM98] 0062	30.5	+566
NGC 5839	32.0	–431
NGC 5845	37.8	–200
NGC 5846A	42.1	+545
NGC 5846	42.4	+88
NGC 6958 ($\sigma = \pm 223$ km/sec)		
APMBGC 341+016-108	12.7	-30

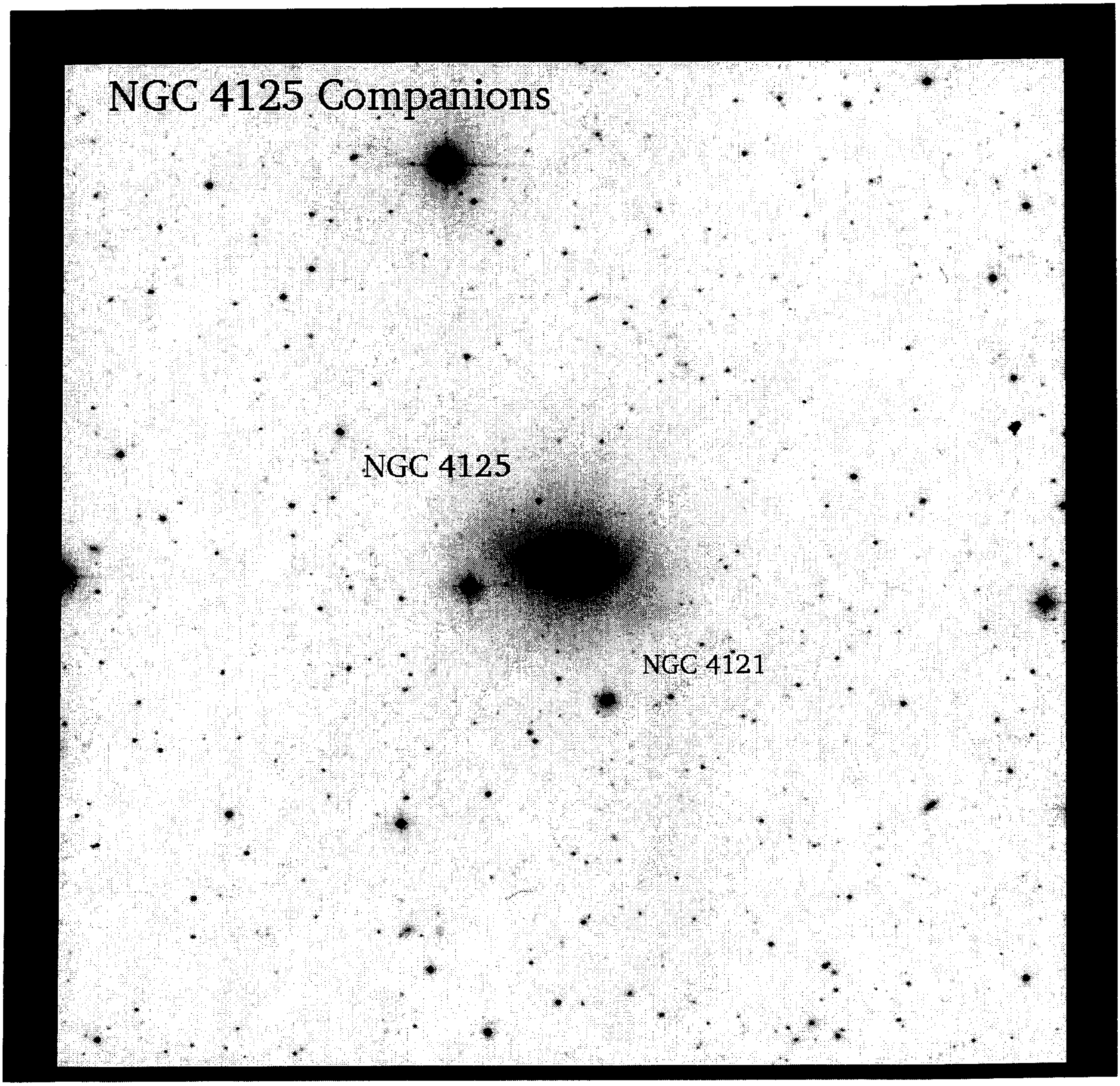

NGC 0584 Companions
2MASXi J0130541-064941
NGC 0584
NGC 0586

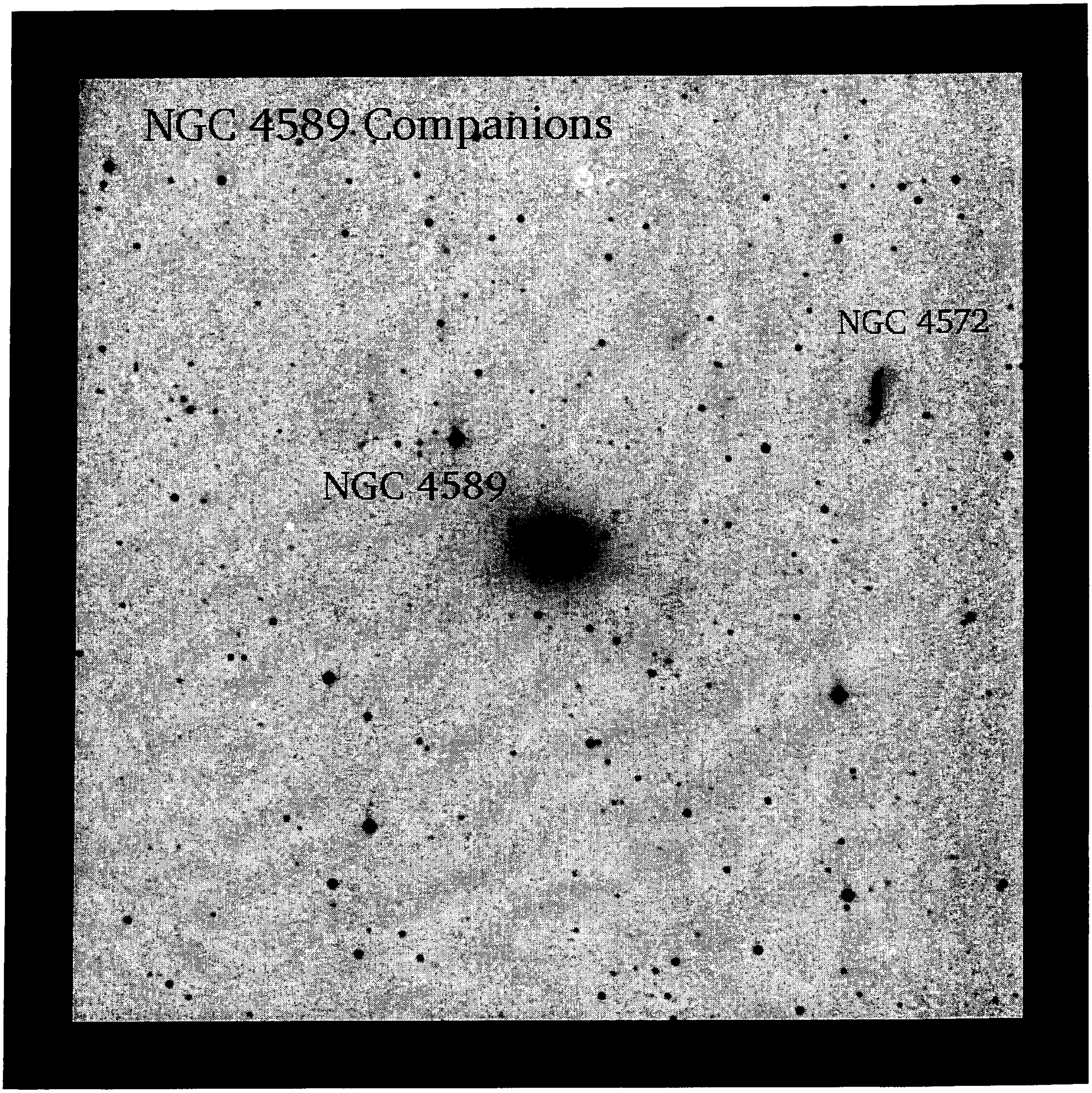

NGC 1052 Companions
[VC94] 023858-0820.4
NGC 1047
2MASXI J0241351-081024
NGC 1052
[KKS2000] 04
NGC 1042

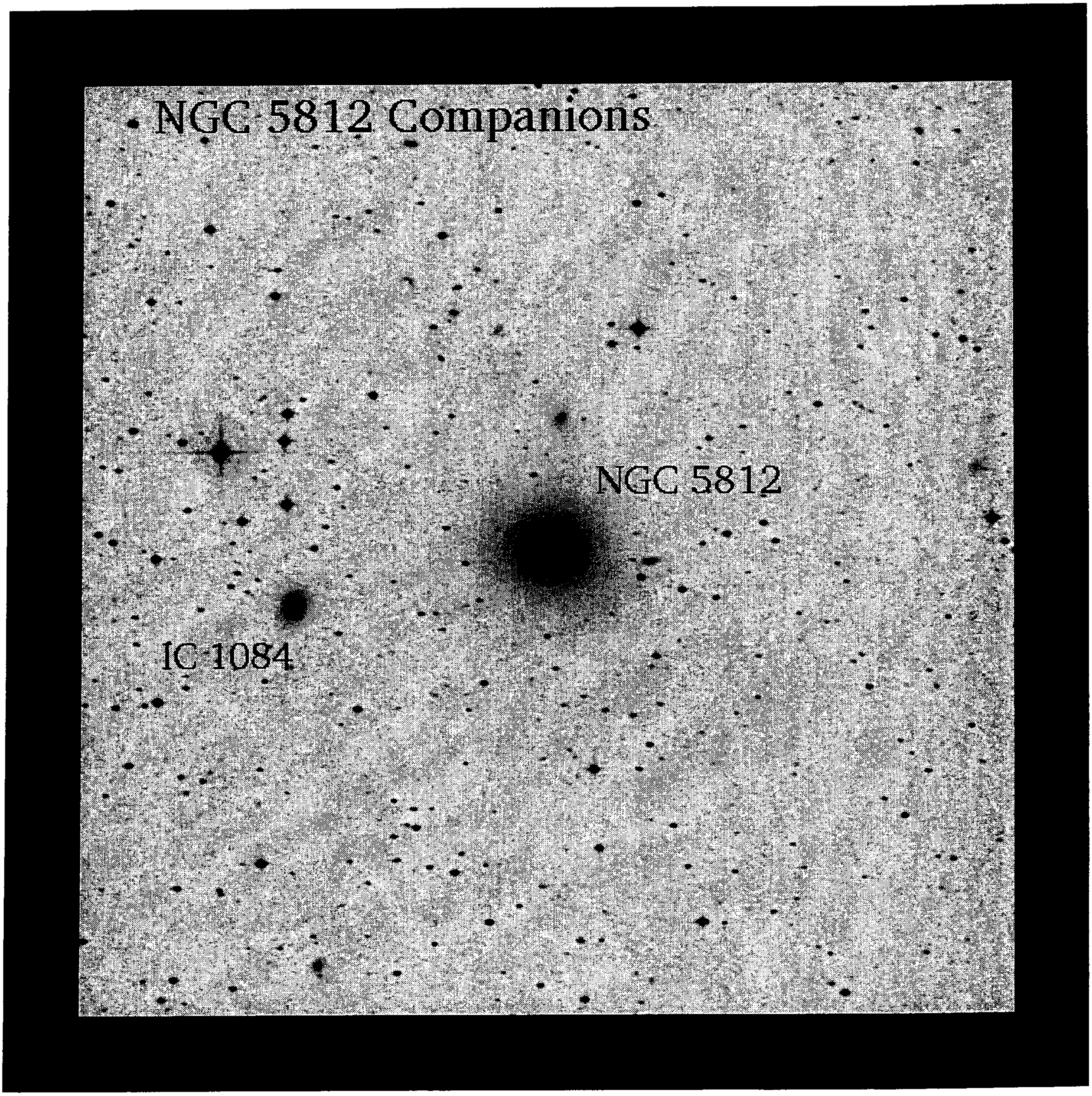

NGC 3348 Companions
NGC 3348
MCG +12-10-079

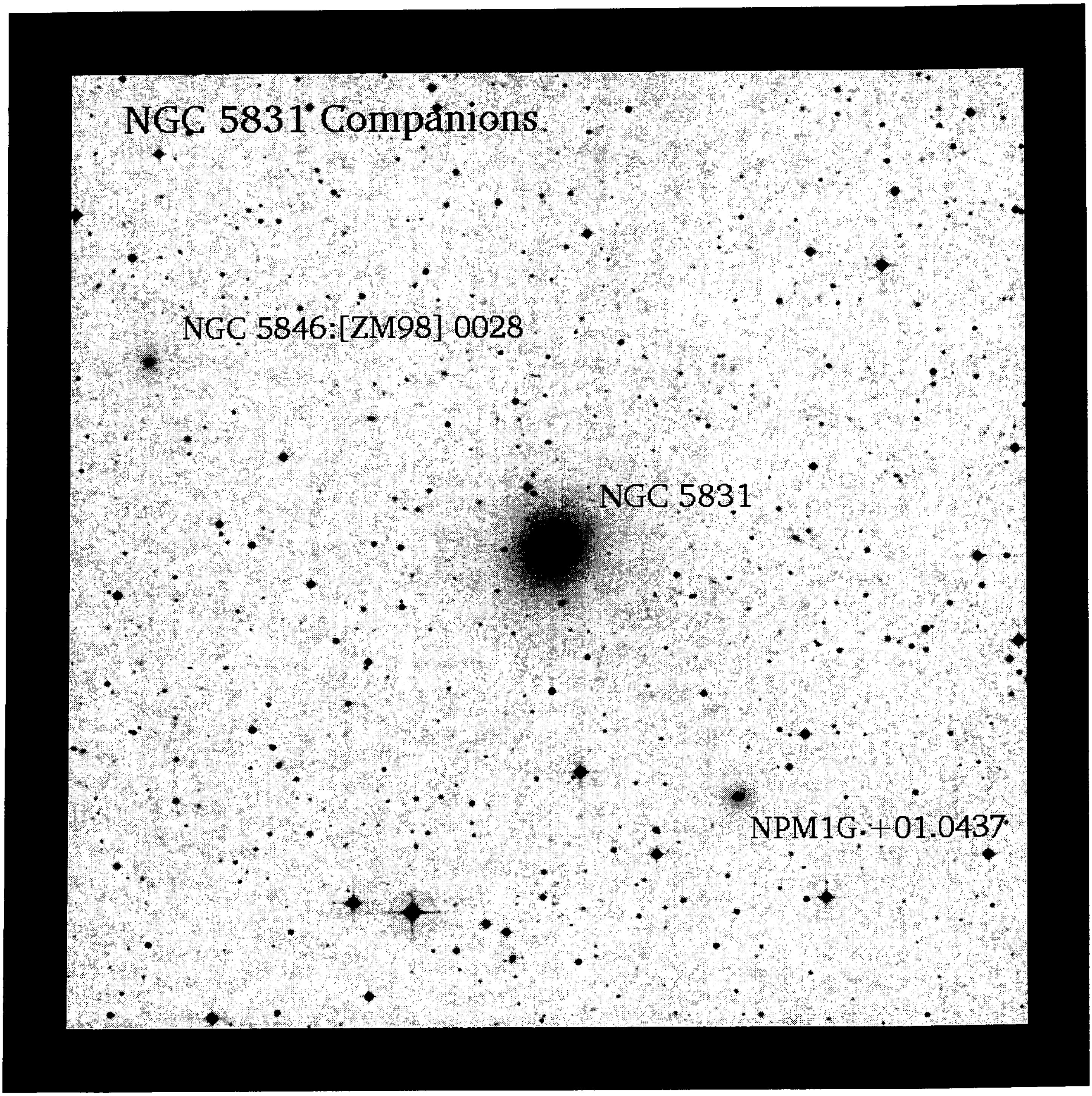

NGC 3640 Companions
NGC 3640
NGC 3641

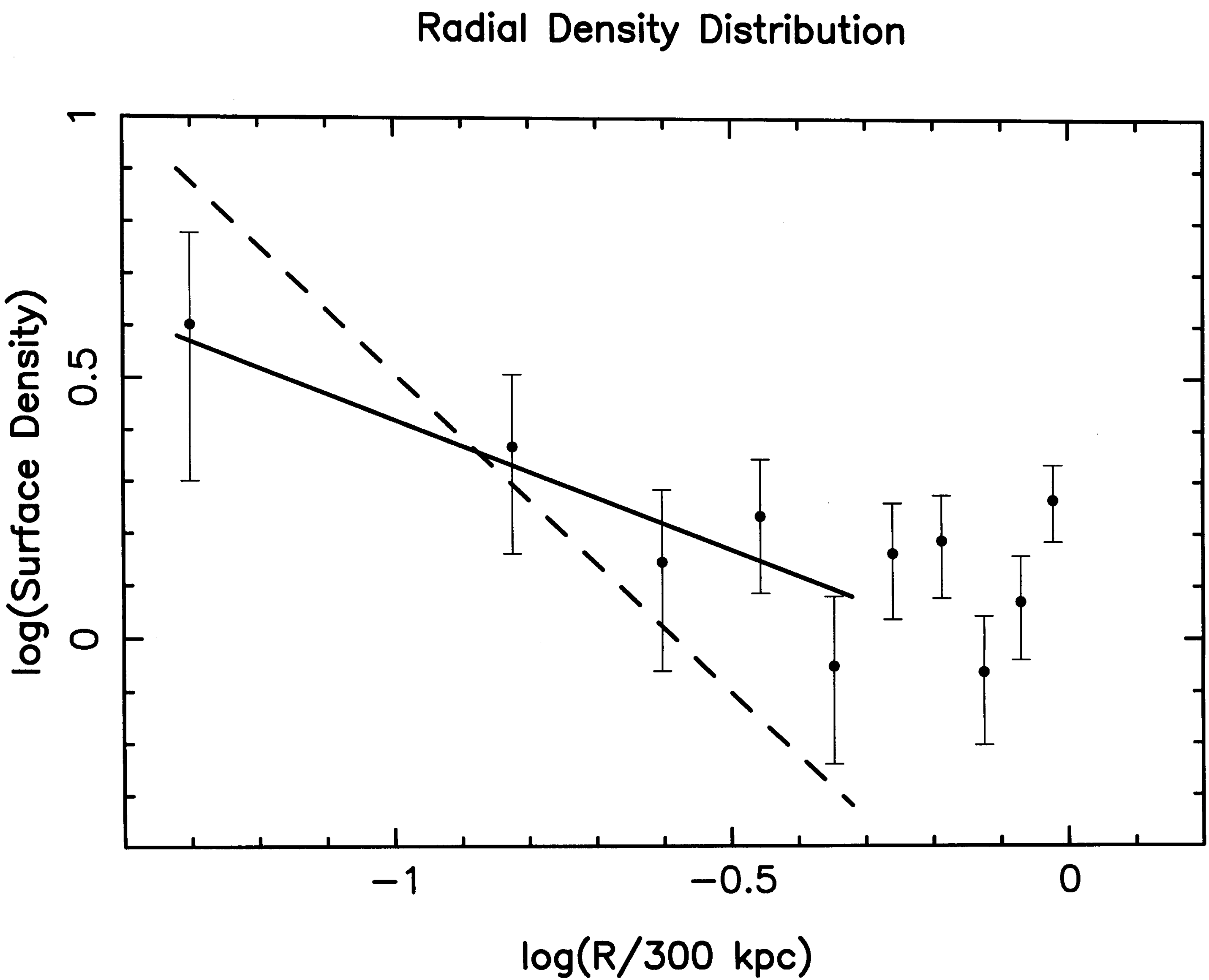

NGC 3818 Companions
NGC 3818
2dFGPS N113Z117

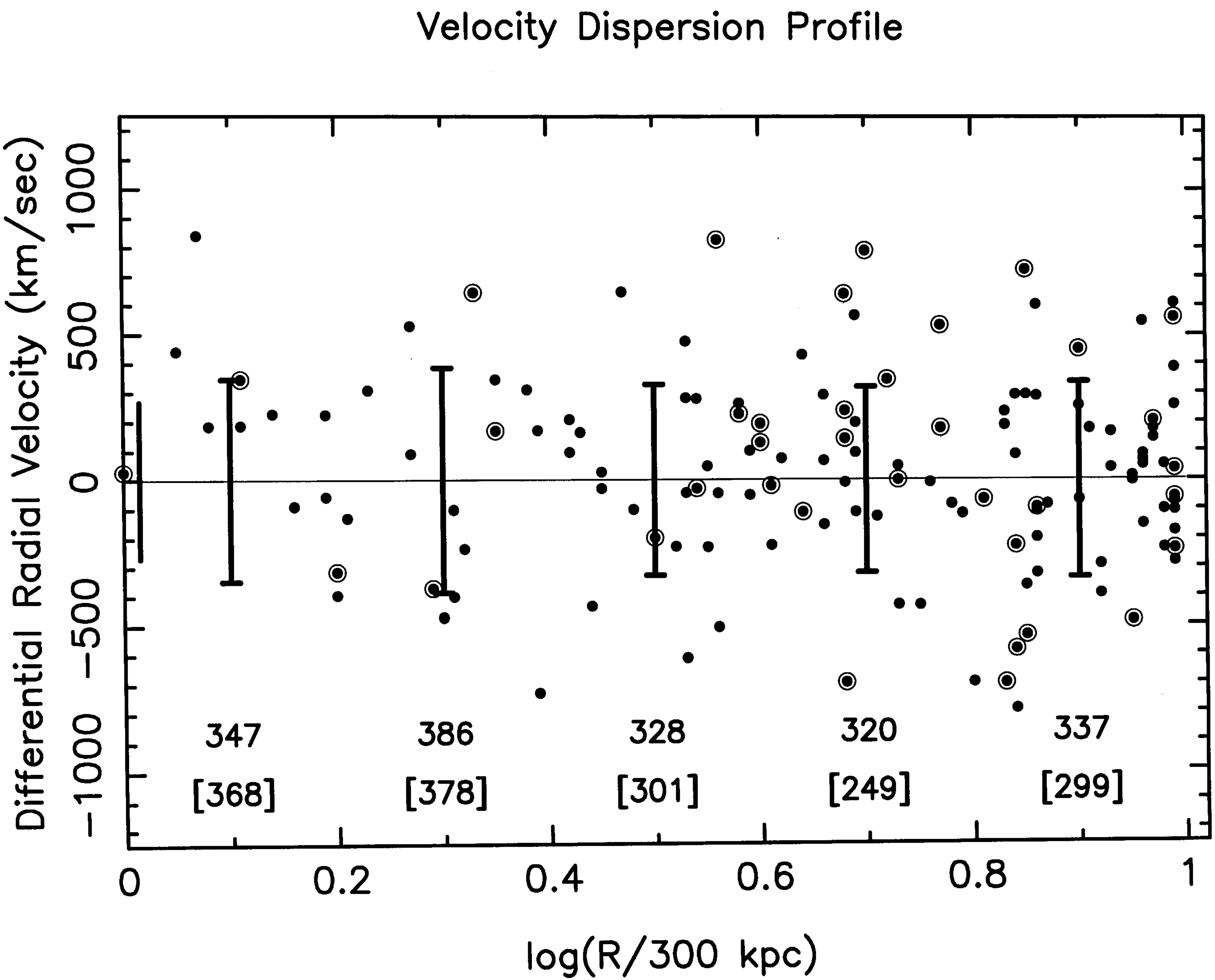

NGC 4125 Companions
NGC 4125
NGC 4121


NGC 4589 Companions
NGC 4572
NGC 4589


NGC 5812 Companions
NGC 5812
IC 1084


NGC 5831 Companions
NGC 5846:[ZM98] 0028
NGC 5831
NPM1G +01.0437


Radial Density Distribution
log(Surface Density)
1
0.5
0
−1
−0.5
0
log(R/300 kpc)



Velocity Dispersion Profile
Differential Radial Velocity (km/sec)
1000
500
0
−500
−1000
0
0.2
0.4
0.6
0.8
1
log(R/300 kpc)
347
[368]
386
[378]
328
[301]
320
[249]
337
[299]